Advanced Beam Instrumentation supporting AARD at the A0-Photoinjector

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Agenda

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- Motivation
- Overview on long. beam diagnostics
- OTR Introduction
- Ongoing Activities
  - Streak Camera
  - *Martin-Puplett* Interferometer
  - OTR Interferometer
  - EOM-based Time-of-Arrival

- Proposed New Activities
  - Long. diagnostics using CTR
  - Long. bunch profile using EOS
  - HOM signal processing
  - Beam tests of a cold ILC cavity BPM prototype
  - Waveguide pickups

Motivation

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- Need a set of reliable basic beam instruments (upgrades required, see also Ray's talk):
  - Intensity, position (orbit), transverse beam size (emittance)
- AARD demands advanced beam diagnostics, in particular in the longitudinal domain to study and observe the bunch dynamics in AARD experiments:
  - Bunch length
  - Longitudinal bunch profile
  - Bunch time-of-arrival
    (wrt. RF phase, or relative between two locations)
- No best "I can do everything" instrument available to fully characterize longitudinal bunch parameters
  - Calibration, measurement range (fs, ps) and time (single/multi shot), (non) invasive, resolution, reproducibility, etc.

Longitudinal Beam Diagnostics

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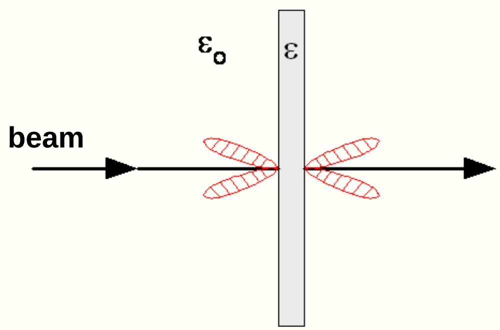
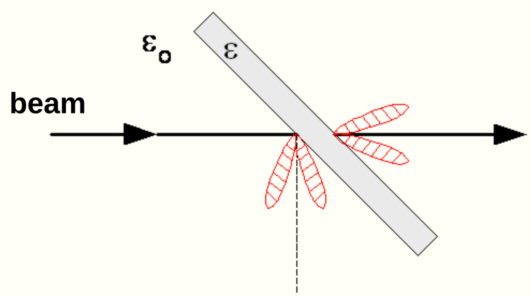
Device	Applicable bunch lengths	Comments
Streak camera **Ongoing activity, Bunch profile**	1 – >100 ps	• Well understood, expensive commercial device • Single bunch, single pass capability (intensity limited) • Dispersion effects dominate at short bunch length measurements • Can provide arrival times and jitter
Martin-Puplett Interferometer Ongoing, length	< few ps	• Slow response, scanning using many macropulses • Susceptible to upstream CSR and wakefields • Missing phase information makes details of the bunch profile difficult to obtain
CTR angular distribution Proposed, length	< few ps	• Parametric measurement of the bunch profile, bunch shape must be assumed • Scanning over many macropulses • Susceptible to upstream CSR and wakefields
Electro-optical sampling Proposed, profile	100 fs – 2 ps	• Single shot capability, fairly expensive, needs a (high power) laser synchronized to the beam • Must understand behavior of electro-optical crystal in the frequency regime corresponding to the expected bunch length • Susceptible to upstream CSR and wakefields
Waveguide pickups Proposed, length	200 fs – 2 ps	• Inexpensive and simple, but calibration very difficult. • Does not give shape information, just rough bunch length

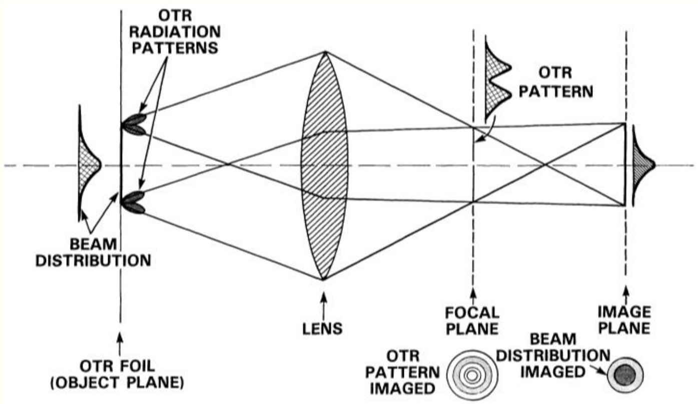
(Optical) Transition Radiation

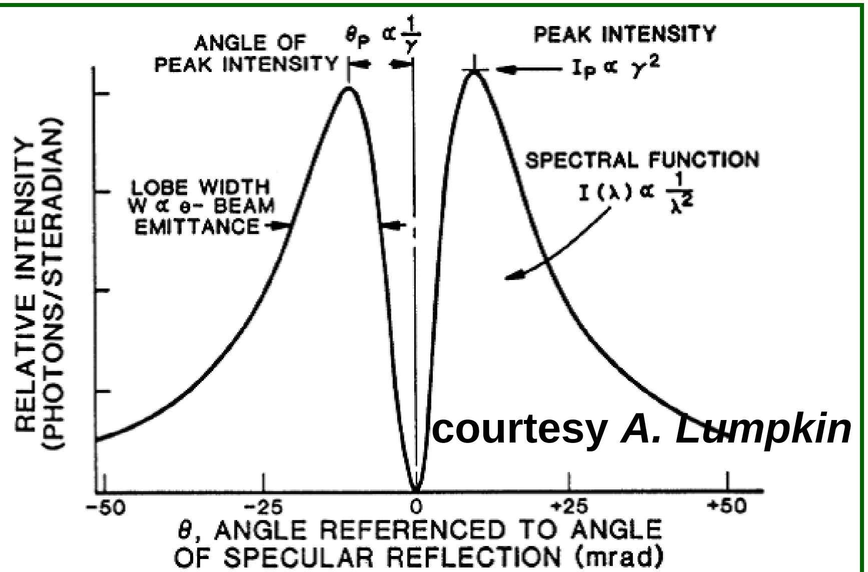


Normal Incidence



Oblique Incidence





courtesy *A. Lumpkin*

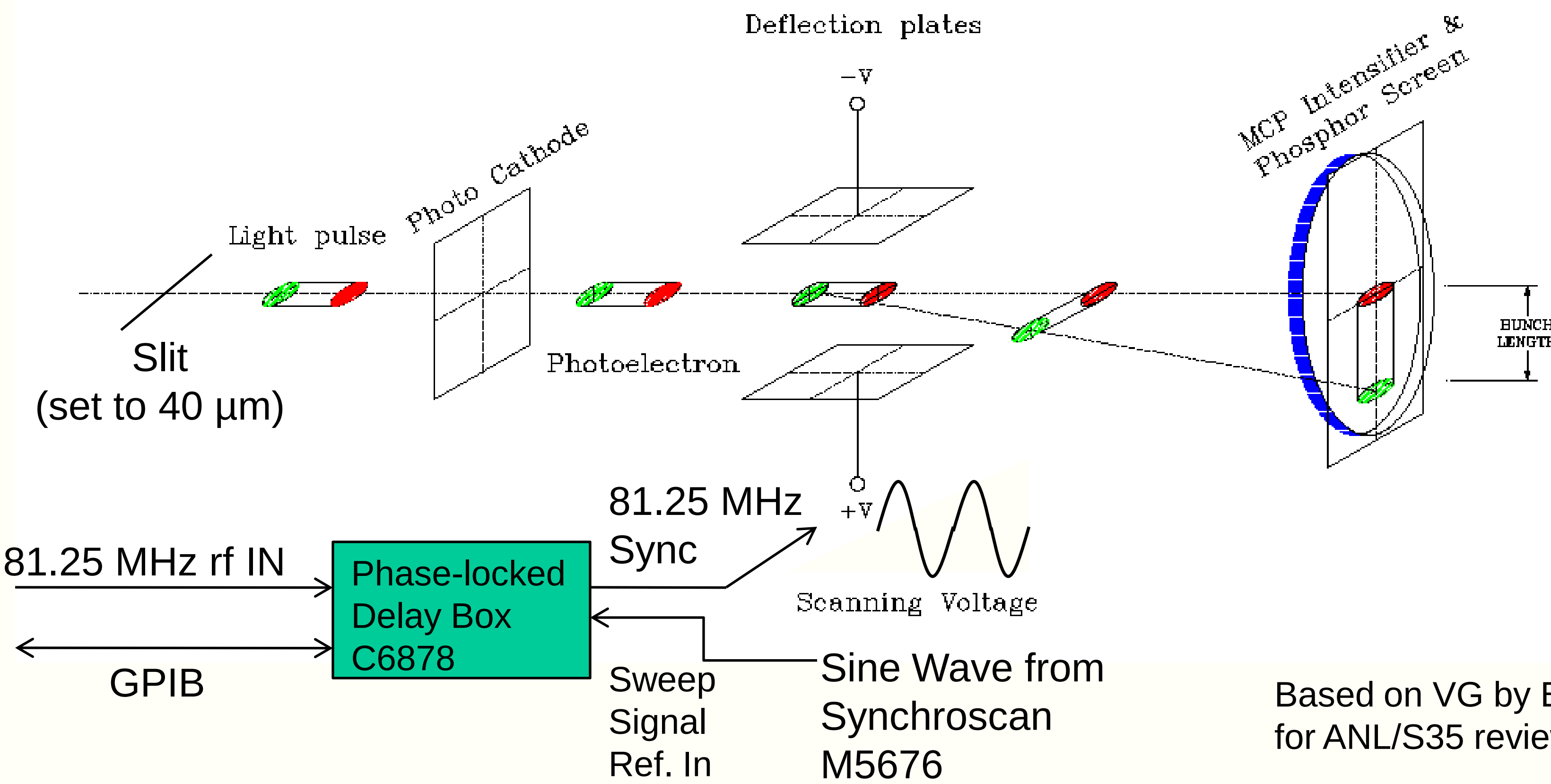
- **Transition radiation**

$$\frac{d^2U}{d\omega d\Omega} \approx I(\omega,\theta) = \frac{e^2}{hc_0}\frac{1}{\pi^2\omega}\frac{\theta^2}{(\gamma^{-2}+\theta^2)^2}$$

  - **Charged particles passes through a media boundary**
  - **Monitoring of trans. beam profile (-> emittance), bunch length and energy**

Streak Camera Principle

- **Dual-sweep streak camera *Hamamatsu* C5680 (1.5 ps FWHM res.)**
- **Addition of M5676 synchroscan plugin module and the C6878 phase-locked delay box enabled new series of experiments at A0.**



Based on VG by B.Yang
for ANL/S35 review

Streak Camera Summary

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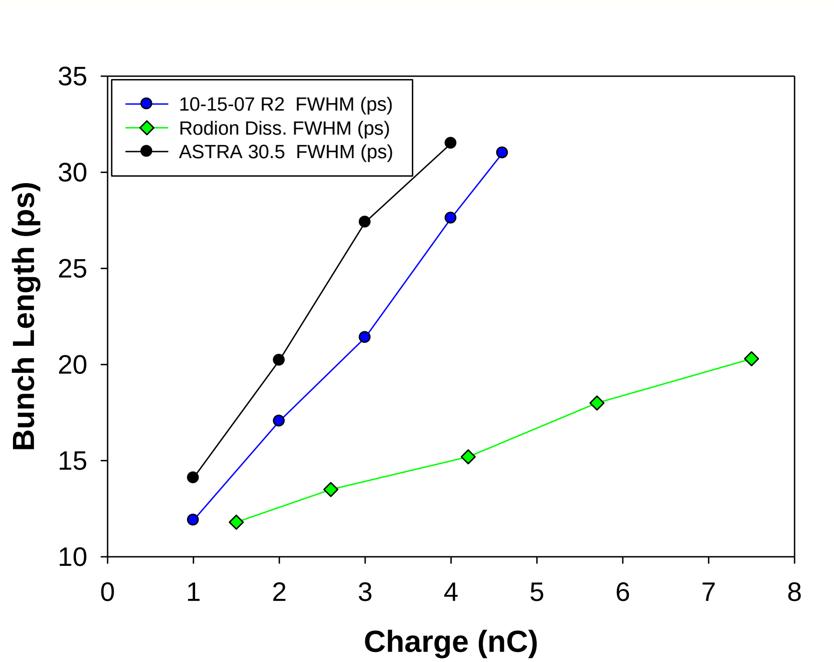
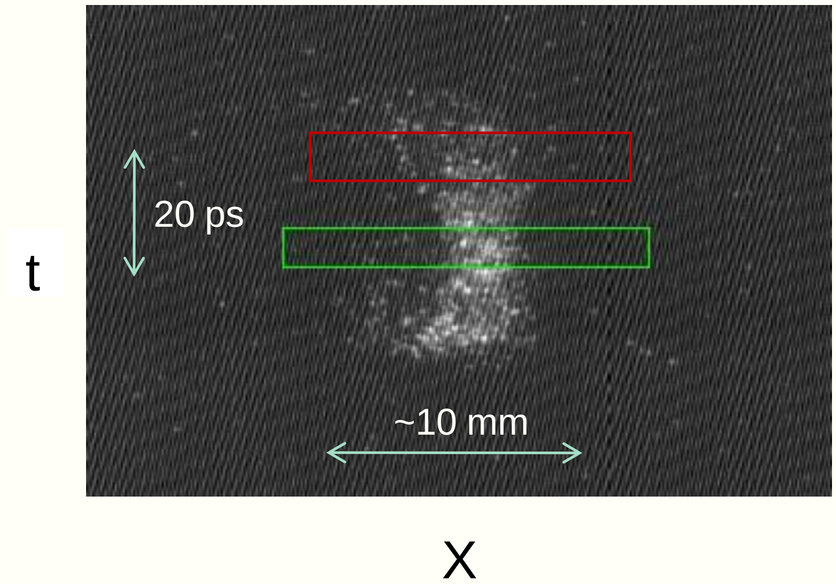
- **Streak camera**
  - Views UV-visible light from a (intercepting or non-intercepting) conversion mechanism, e.g. OTR, OSR to observe the bunch.
  - Provides a 2-D bunch profile, allowing sliced measurements:
    - Vertical axis -> time axis
    - Horizontal axis: preserved (spatial, energy, spectral)
- **Features**
  - Synchroscan unit (81.25 MHz, phase-locked to master oscillator)
    - ~1 ps RMS jitter
    - Synchronous summing of micropulses (statistics, intensity)
  - Delay unit provides long term stability
  - Dual-sweep allows simultaneous observation of micropulses
- **Resolution**
  - 1.5 ps FWHM (monochromatic), larger for broadband light

Streak Camera Results

- **Bunch length elongation with micropulse charge and slice beam-size effects (50%) at 4 nC observed.**





Lumpkin,Ruan: BIW08

Steak Camera Results (cont.)

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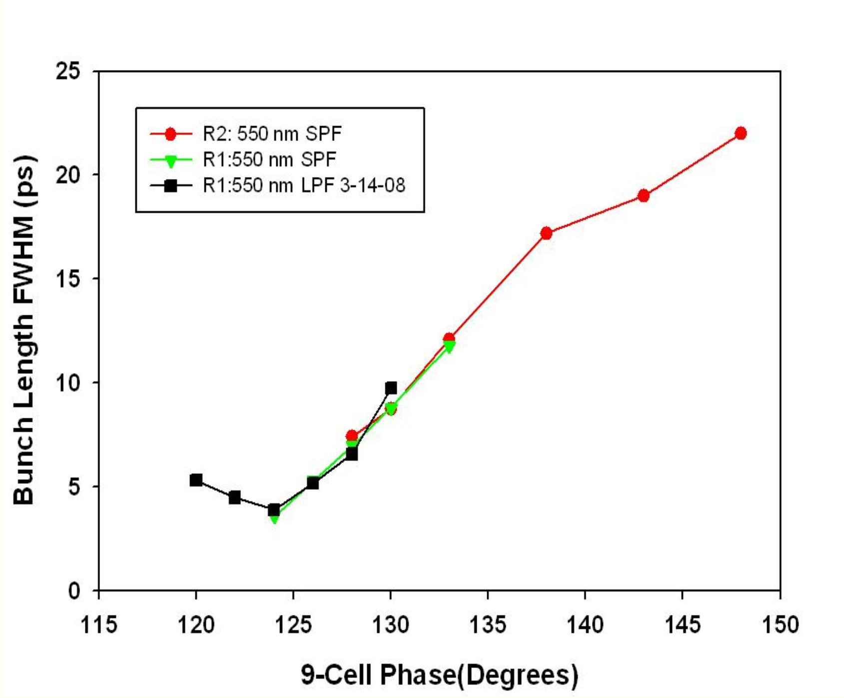
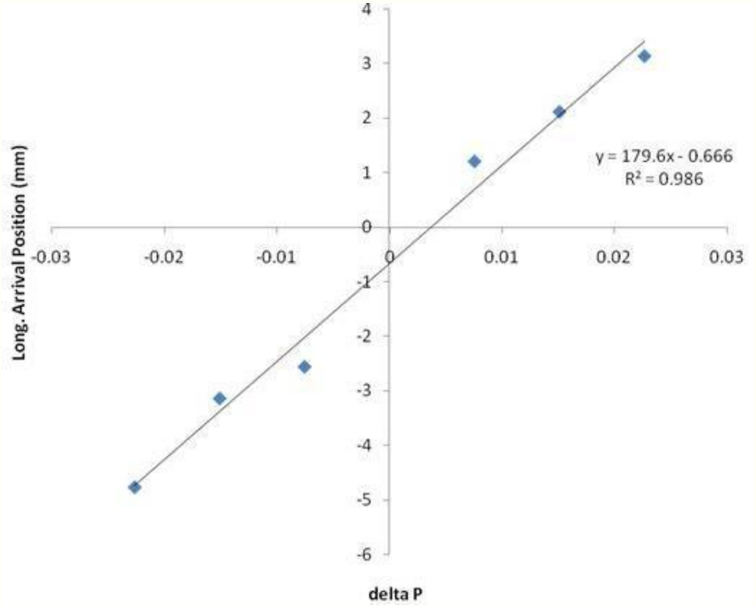
- **Bunch compression and transit time changes for different momenta in double doglegs were measured.**



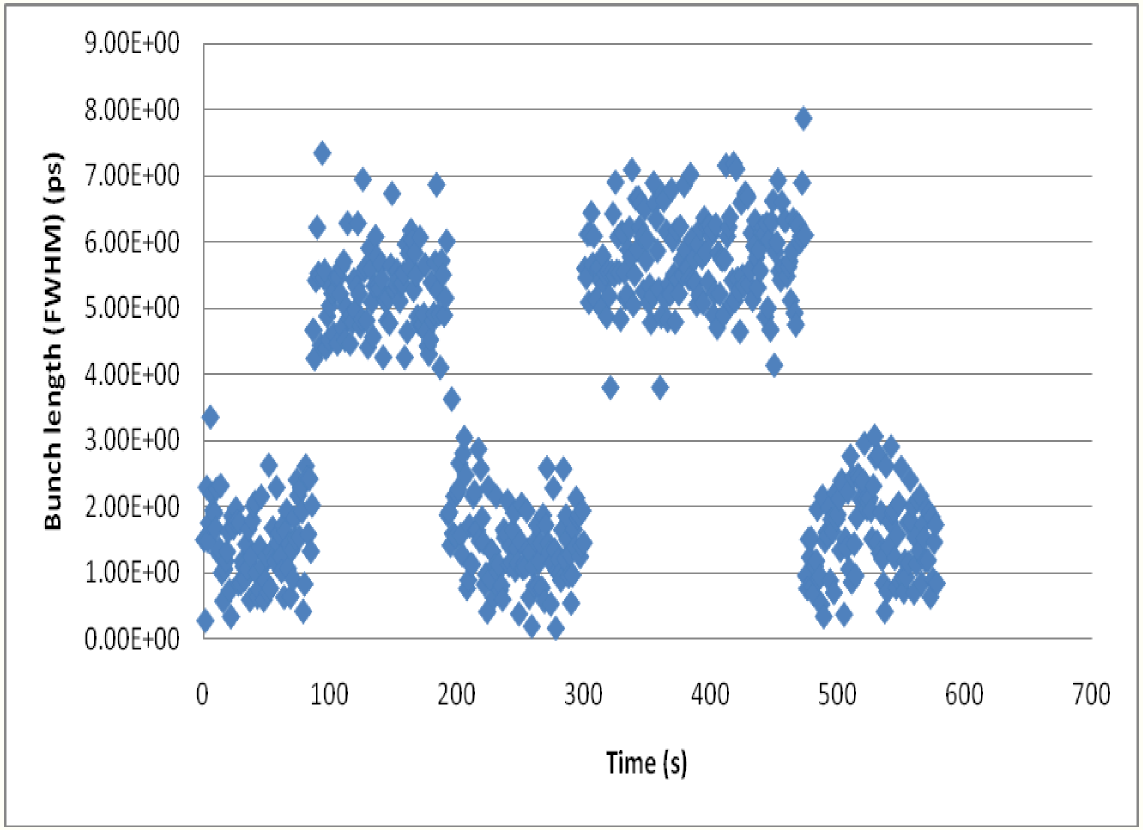


The line is a fit showing that R_{56} is 0.18 m

Lumpkin,Ruan: BIW08

Streak Camera Results (cont.)

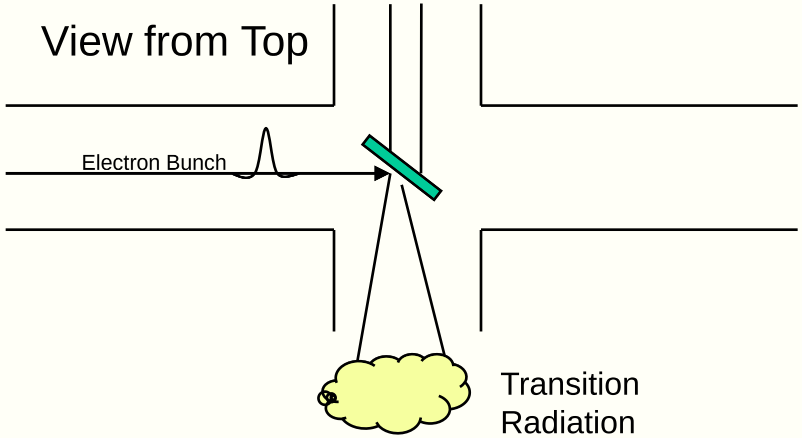
- **Emittance exchange results in bunch compression.**

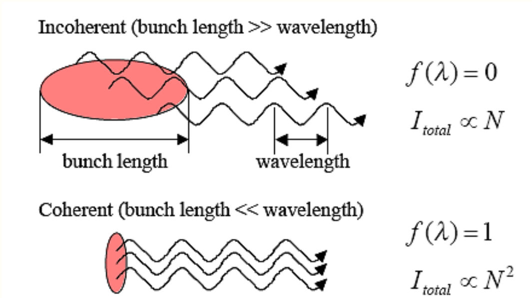


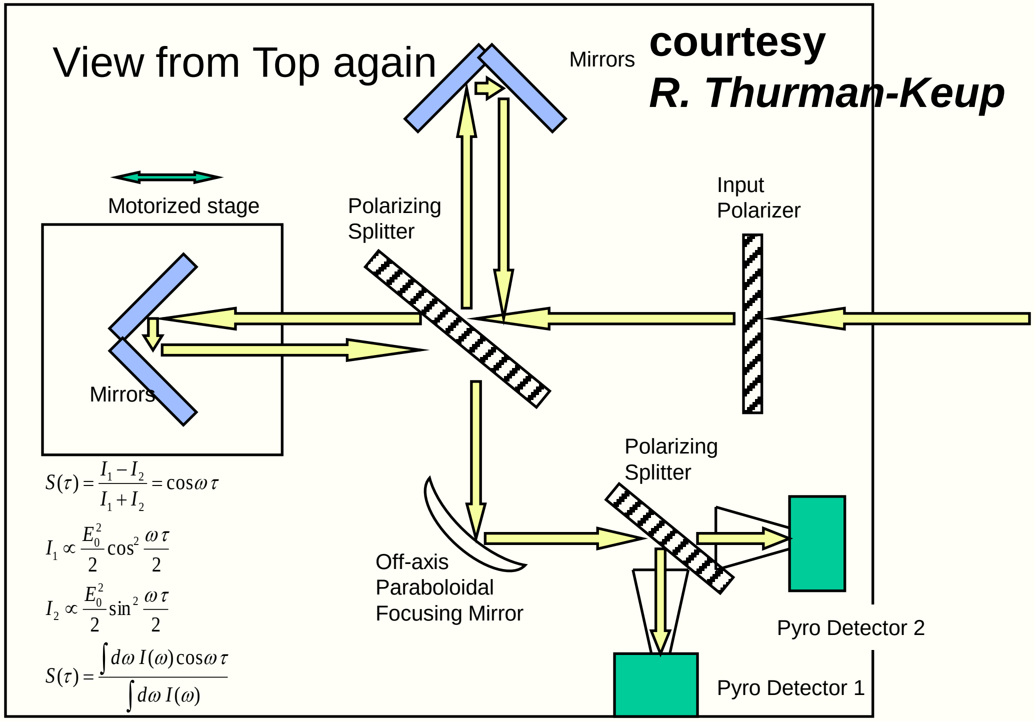
← 5-cell off

← 5-cell on

Martin-Puplett Interferometer







courtesy
R. Thurman-Keup

$$I(\omega)=I_0(\omega)\Big(\underset{\uparrow}{\overset{\text{Incoherent}}{N}}+\overbrace{N(N-1)\left|F(\omega)\right|^2}^{\text{Coherent}}\Big)$$

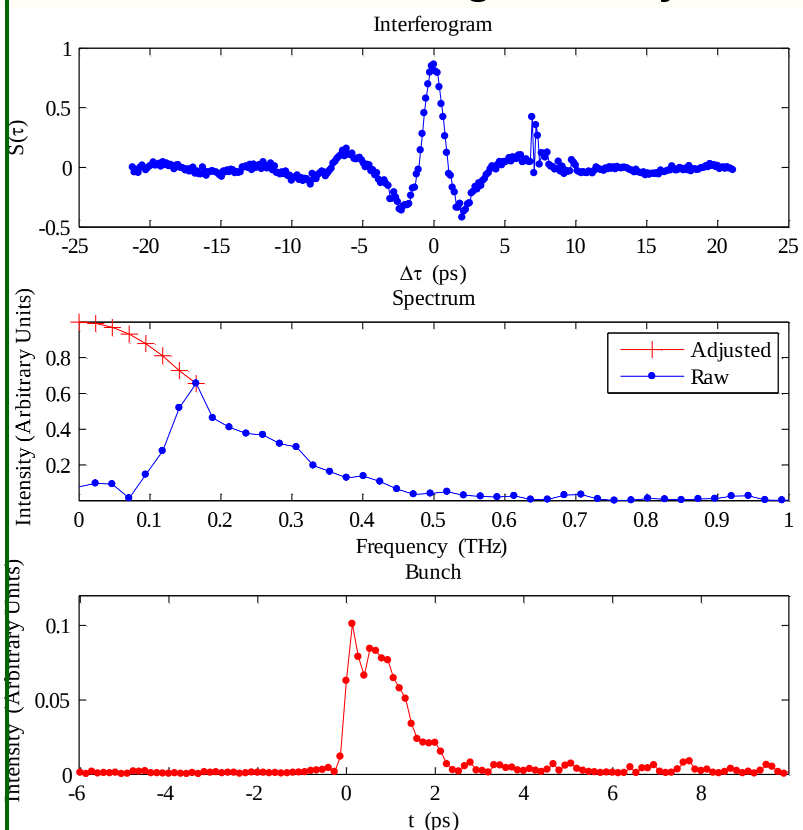
$$F(\omega)=\frac{1}{Q}\int d^3x\,\rho(\vec{x})e^{-i\omega(\vec{x}\cdot\hat{n})}$$

- **Martin-Puplett interferometer**
  - **Needs many beam pulses to resolve the temporal convolution**
  - **Difficult to calibrate the detectors**

MP Interferometer Results

- **Measurement experiment 2008:**
  - **Using improved pyroelectric detector (DESY) with suppressed interference**
  - **Measured spectrum does not show interferences**
- **Bunch length measurement results (deflecting mode cavity on/off), and comparison:**
  - **Autocorrelation with ratio = 0.69**
  - **Reconstructed bunch ratio = 0.43**
  - **Streak camera ratio = 0.66**
- ***MP* issues**
  - **Detector response (low freq.) and calibration**
  - **Diffraction effects at lower wavelength**

Emittance Exchange Cavity On



MP Interferometer: Next Steps

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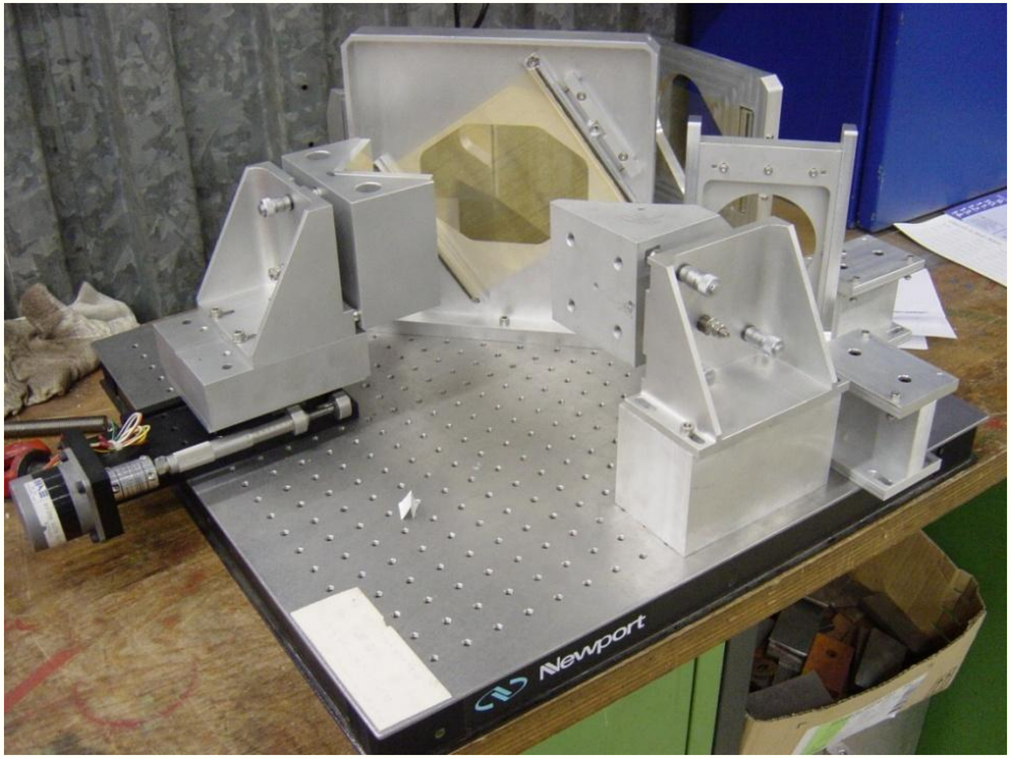
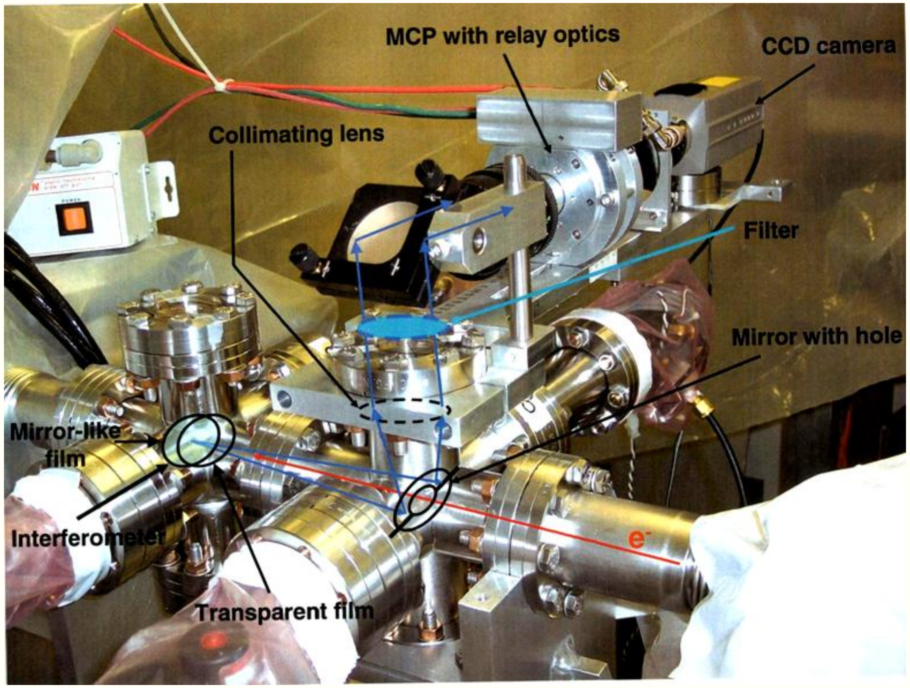


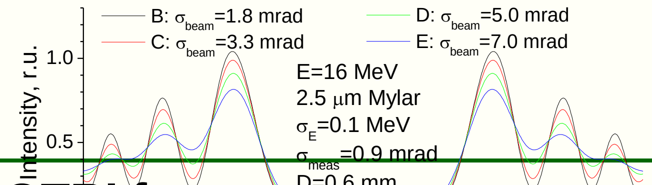
Martin-Puplett Interferometer
(borrowed from DESY)

- **Plans**
  - **Calibration of the pyroelectric detector frequency response**
  - **Experiments with other detector types**
    - **Golay cell**
    - **Schottky detector**
  - **Reproduction and improvements of the *MP* interferometer hardware (borrowed from DESY).**

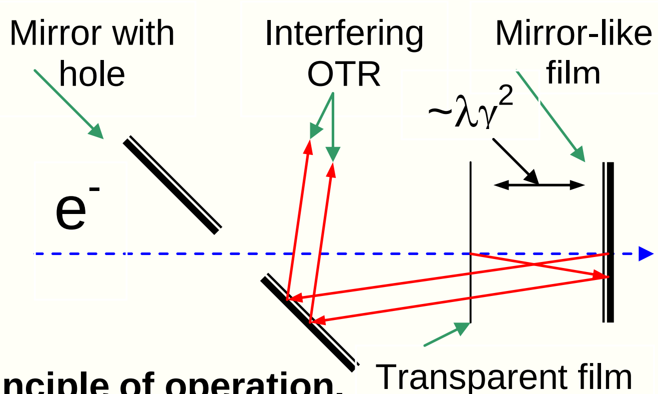
OTR Interferometer (OTRI)



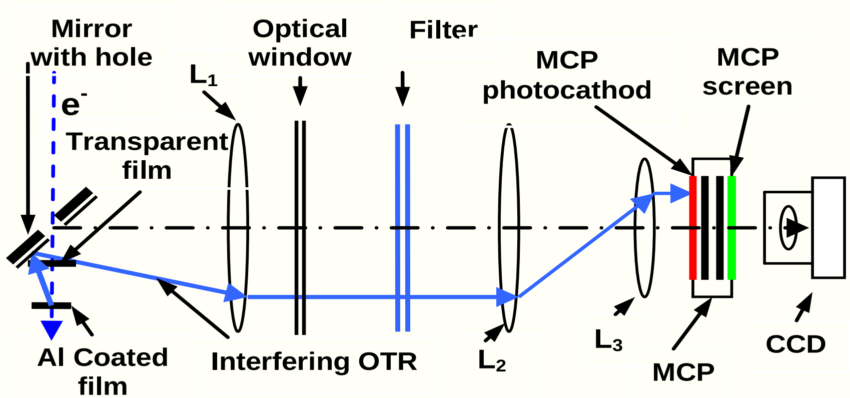
OTRI apparatus at the A0 Photoinjector.



- **OTRI features:**
  - **Beam divergence measurement**
  - **Beam energy (better accuracy)**
  - **Single shot measurement (no scanning)**

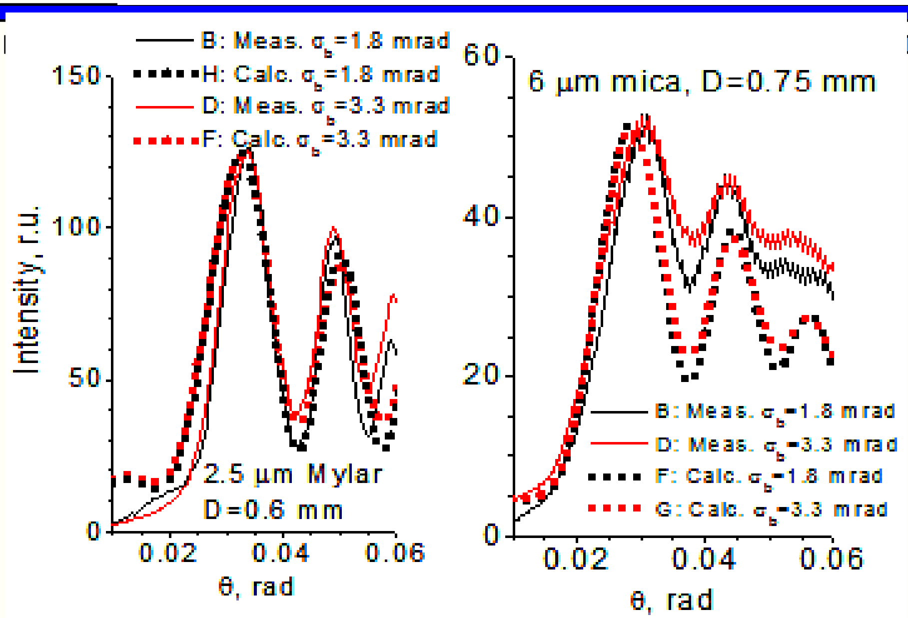


OTRI principle of operation.

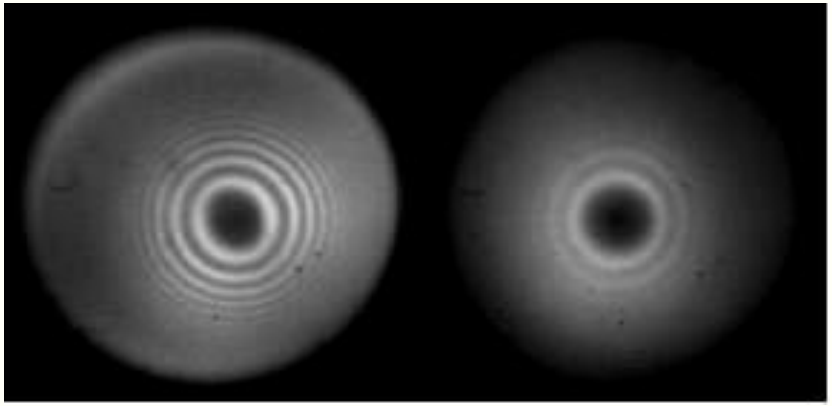


OTRI normal incidence setup & optical readout.

OTRI Results



Measured (solid lines) and computed (dots) fringes for the Mylar (left) and Mica (right) -based interferometers at normal incidence, 16 MeV beam with the energy spread of 0.6% and the readout resolution of ≈0.9 mrad.



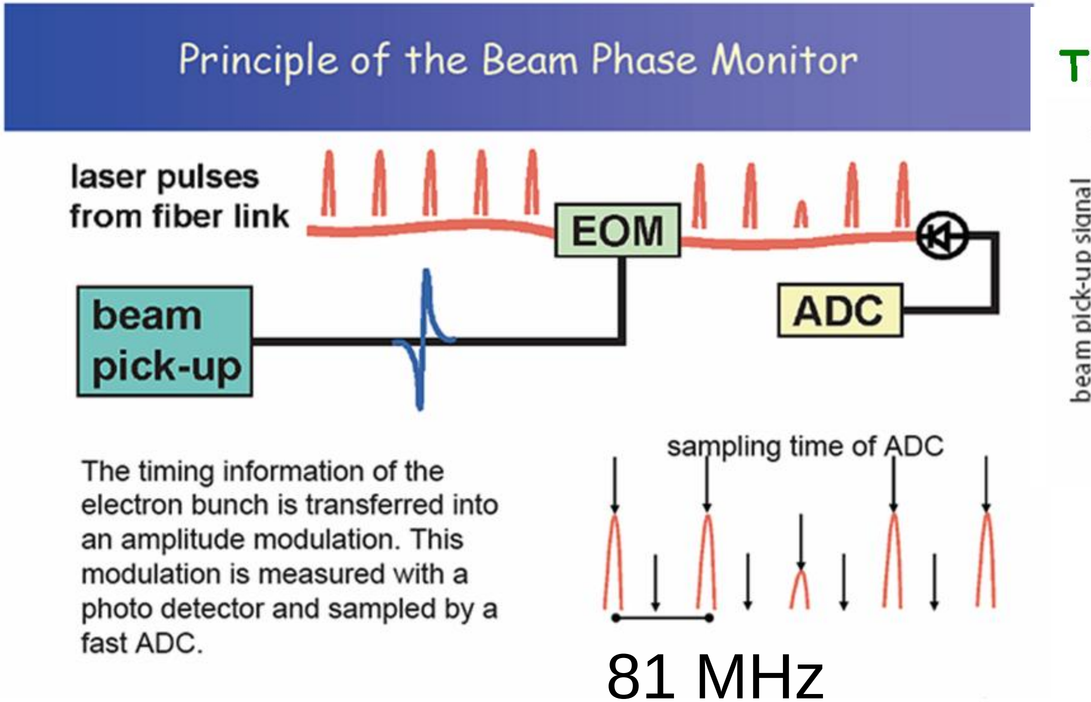
The interference pattern obtained at 45^0 incidence setup with Mylar (left) and Mica (right) -based interferometers at the beam energy of 16 MeV.

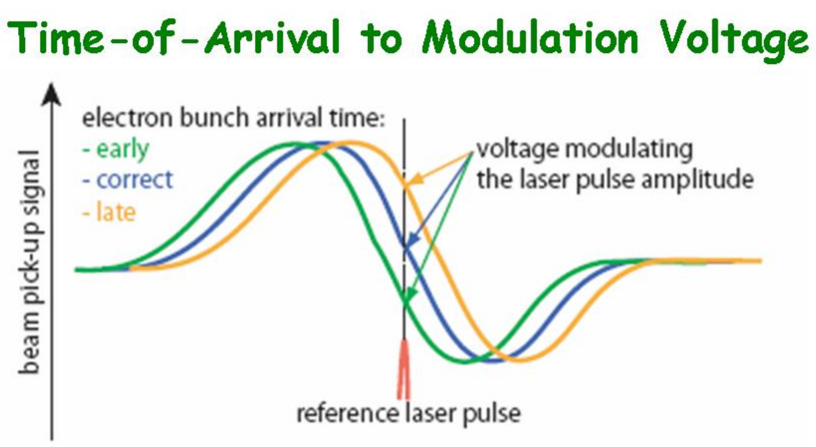
- **Next steps**
  - Experiment with thinner foils
  - Beam divergence measurements at higher beam energies
  - Measurements in the EEX line?!

- **Results**
  - Measurements taken with 2.5 µm Mylar and 6 µm Mica double foils
  - Mylar foils show very good agreement with simulation!
  - Beam divergence measurement accuracy ~ 15 %

Time-of-Arrival / Beam Phase

- To quantize long. beam dynamics a sub-ps resolution bunch-by-bunch time-of-arrival measurement is required!
- An electro-optical modulator (EOM) fed by femto-second fiber laser pulses utilizes the sampling of a high slew-rate pickup signal.
- The bunch time-of-arrival is referenced to the RF master oscillator.



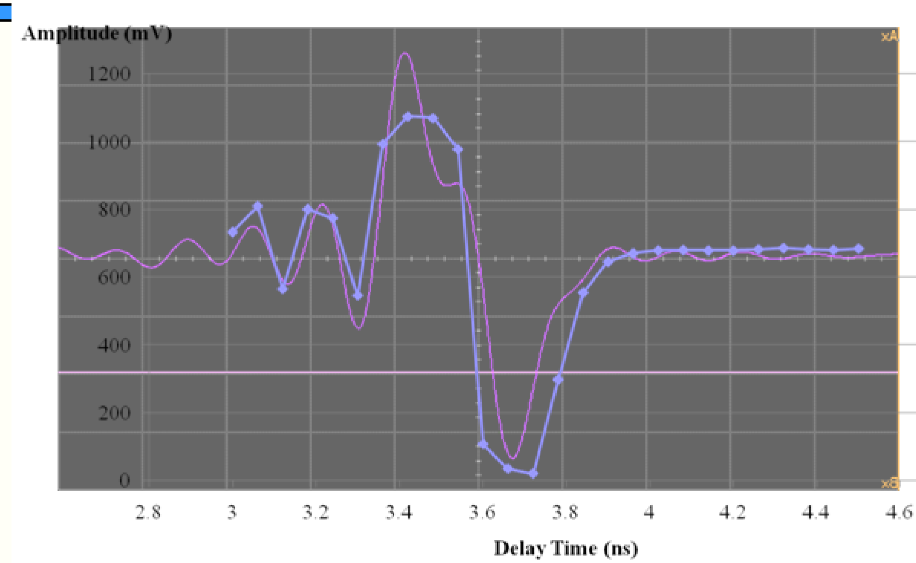


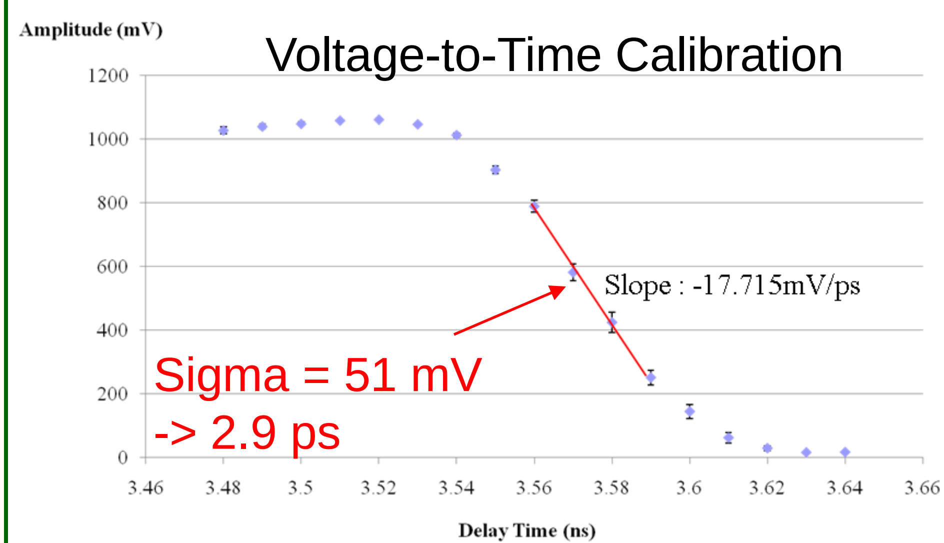
courtesy *F. Loehl, DESY*

Modulate laser pulse with zero-crossing voltage from beam pickup.

TOF Preliminary Results

- **Initial results:**
  - **EOM setup established**
  - **First measurements taken**
  - **Resolution limited by**
    - **Noise & jitter sources (EMI, 81.25 MHz master)**
    - **Pickup response**
    - **Long cable runs (> 50 ft)**
    - **Fiber laser PLL lock**
  - **Resolution: ~3 ps (RMS)**
- **Next Steps**
  - **Identify and improve jitter source, improve system resolution (100-200 fs)**
  - **Improved beam pickup**
  - **New location with shorter cable runs (in the cave?!)**

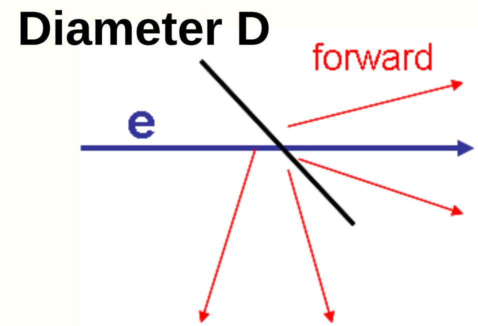




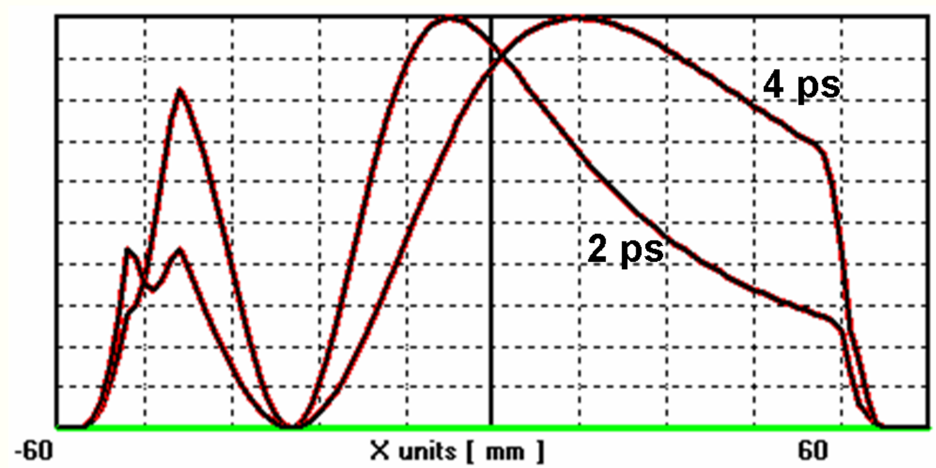
Long. Diagnostics using CTR

- Large target D >> $\gamma\lambda$ and far field L >> $\gamma^2\lambda$
  - Angular distribution does not depend on frequency
  - Measurement using OTR (visible)
- Small target D < $\gamma\lambda$ and/or near field L < $\gamma^2\lambda$
  - Angular distribution depends on frequency
  - Measurement using coherent TR (CTR) (far-infrared)
- **Transition region D ~ $\gamma\lambda$**
  - **Angular distribution sensitive to bunch length**
  - **Tune D as function of γ and λ to be in this transition region**
  - **Map angular CTR distribution of measure the bunch length**

Proposal from R. Fiorito and A Shkvarunets, *University of Maryland*



Coherent TR distribution for 16 MeV electrons at A0 for two bunch lengths



Results from PSI-SLS (100 MeV)

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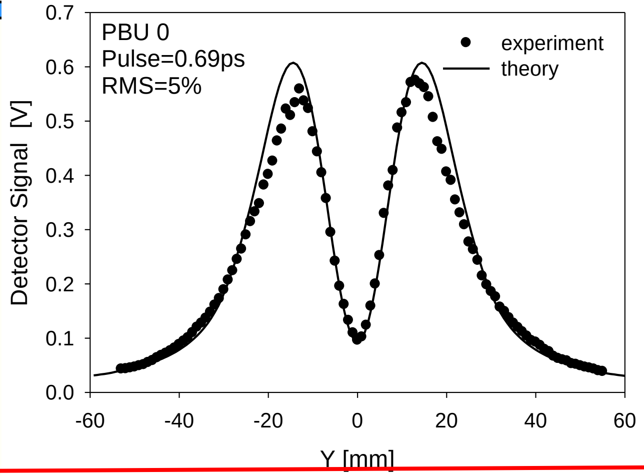
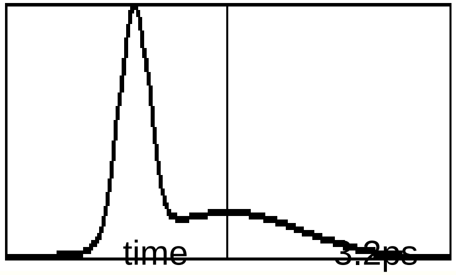


Energy distribution of CTR

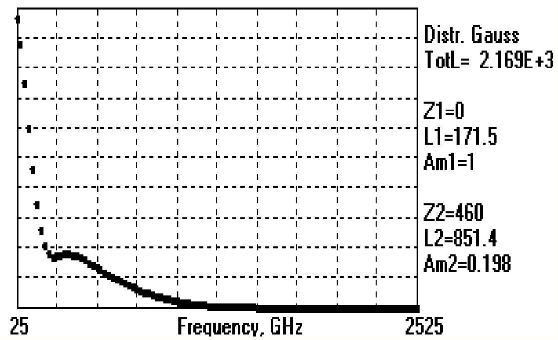
Single Gaussian bunch fit

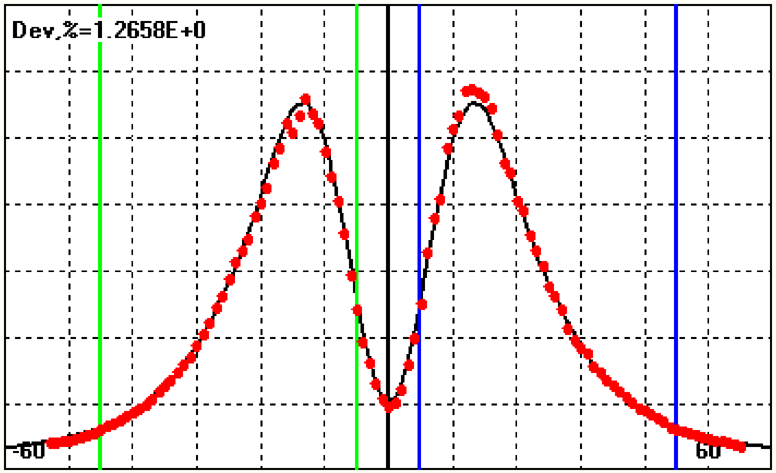
0.69ps, RMS=5%



Double Gaussian bunch fit, RMS=1.26%,

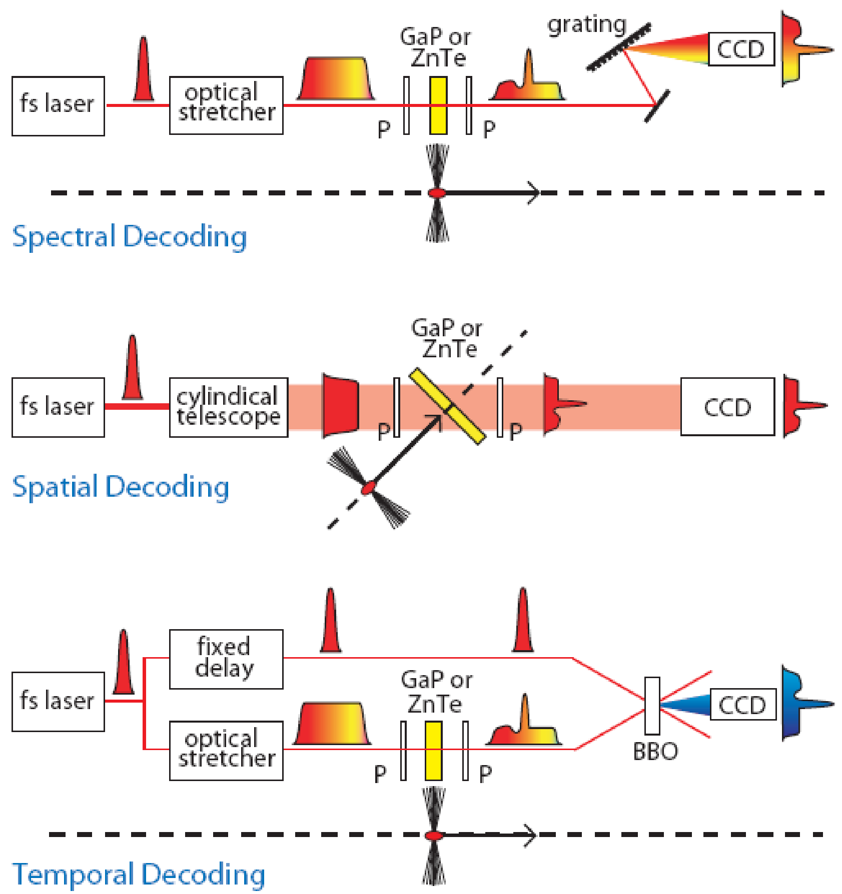
0.57ps, Am=1;
2.84ps, Am=0.2, Shift=1.53ps





Reference: paper WEPC21, DIPAC 07

Electro-Optical Sampling (EOS)



Three common single shot EO detection techniques to measure sub-ps bunch length

- All 3 single shot scheme are realized
- Temporal decoding resolve bunch length <100 fs using Ti:sapphire laser and GaP crystal at DESY
- At DESY, deflecting mode cavity proved the effectiveness of EO techniques
- Most current EO experiments are done on high energy electron beams
- Most current EO efforts are focused on electron bunch length less than 200 fs.

Comparison of EOS Techniques

	Spectral Decoding	Temporal Decoding	Spatial Decoding
Pros	• Simple laser system • Single shot measurement • High repetition rate	• Large time window • High resolution (110 fs) • Single shot measurement	• Simple laser system • Single shot measuement • High resolution (160 fs) • High repetition rate
Cons	• Limited resolution (200 fs) • Distorted signals for e^- bunches < 200 fs	• Complex laser system (mJ laser pulse energy) • Low repetition rate	• Complex imaging optics • Good for clocking, but tough to get the e^- bunch information

- **For the current A0 research requirements and laser availability we will focus on the spectral and spatial decoding techniques.**

Proposed EOS Activities

1. **Measure longitudinal bunch information of low energy electron beams**

EO resolution $\Rightarrow$ $\dfrac{2R}{\gamma c}$

Here R is the distance between crystal and electron bunch center

$\Downarrow$

- What will happen when γ is low?
- Can we deconvolute the signal?

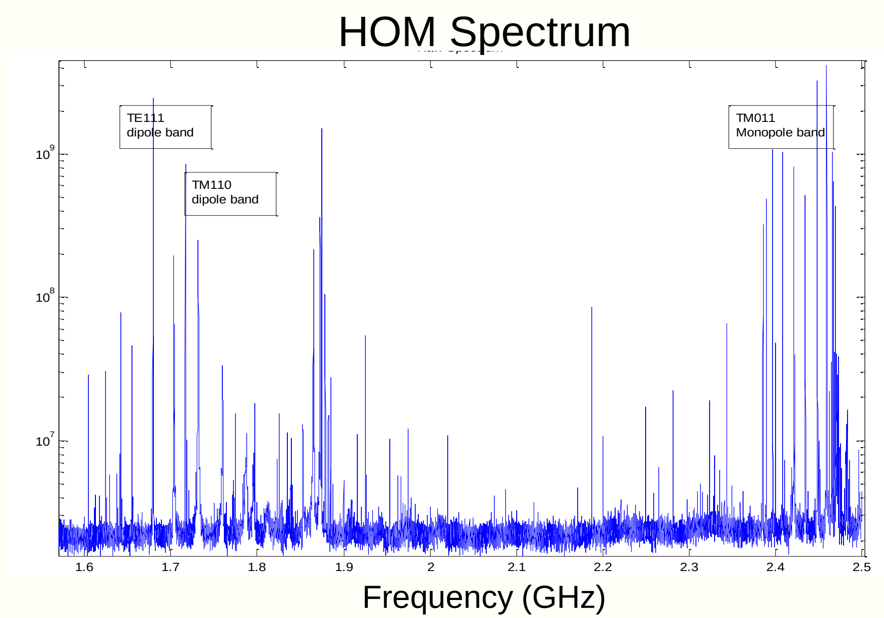
Current energy in A0 and upgraded A0 is a very good fit for this study

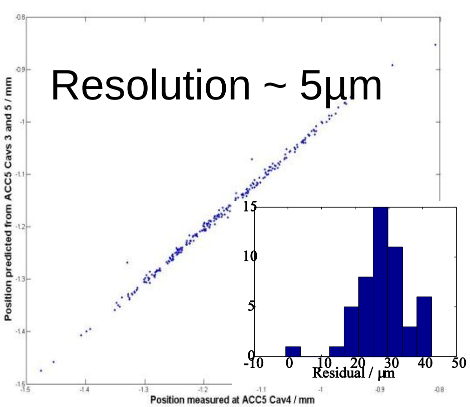
2. **Investigate the use other laser wavelengths, via fiber lasers, for EO sampling at these bunch length.**

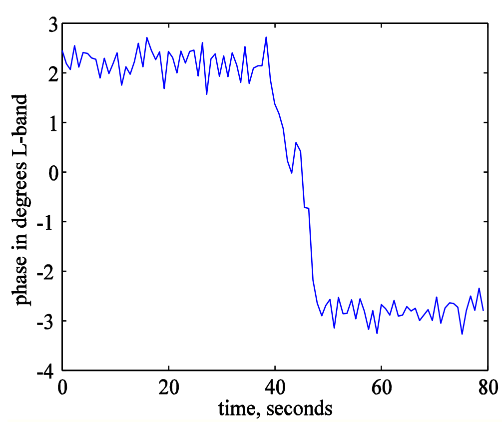
	Ti:Sa Laser	Fiber laser
Cost	High	Low
Transport	Free space Complicated	Fiber Easier
EO study	Successfully Done	?

Recent simulations show that a fiber laser based EOS is feasible!

HOM Signals for Beam Monitoring







- **HOM as BPM**
  - **TE_{111-6} narrow band read-out**
  - **Beam-based calibration data, to orthogonalize the polarization planes of the excited eigenmodes per SVD algorithm.**
- **HOM as phase monitor**
  - **Comparison of the leaking 1.3 GHz fundamental (TM_{010}) to the first monopole HOM (TM_{011})**
  - **Broadband Scope analysis**
  - **<0.1^0 @ 1.3 GHz resolution (equiv. ~200 fs RMS)**

HOM Development & Analysis Plans

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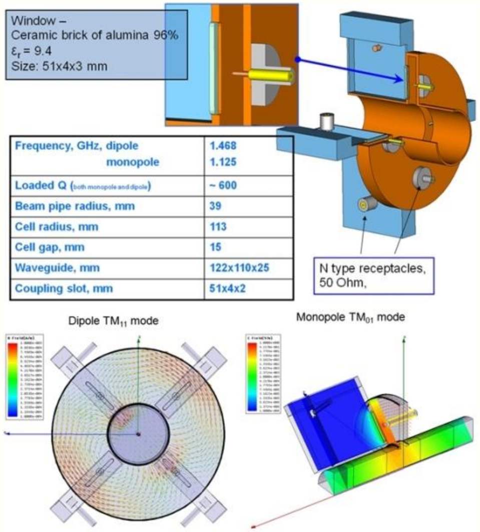
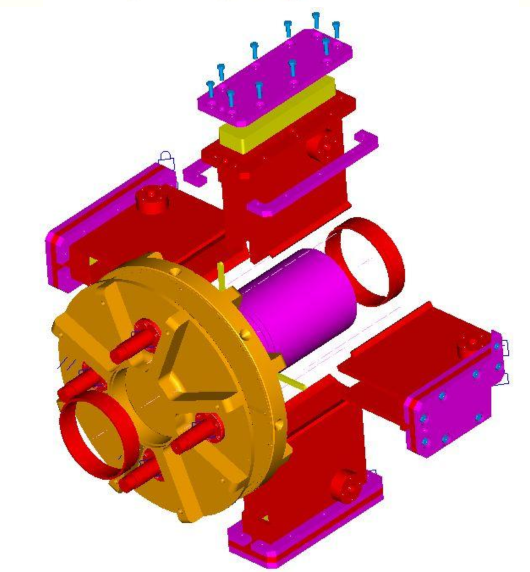
- Develop read-out hard- and firmware for HOM Analysis
  - Narrowband System:
    - Low-noise, high-IP3 downmix hardware based on SLAC/KEK/DESY ILC collaboration experience
    - Try to to incorporate flexibility, tunable to downmix different dipole and possibly monopole bands
    - Low cost per channel custom VME digitizers, capable of processing the HOM signals using the onboard FPGA
  - Broadband system: High-speed oscilloscope
- HOM Analysis
  - The above instrumentation can be used to provide beam position, trajectory, and phase measurements to optimize performance.
  - Because the HOM spectrum is a function of the cavity shape, the observed modes provide a powerful cavity diagnostic for study and simulation.

Other Activities



Frequency, GHz, dipole monopole	1.468 1.125
Loaded Q (both monopole and dipole)	~ 600
Beam pipe radius, mm	39
Cell radius, mm	113
Cell gap, mm	15
Waveguide, mm	122x110x25
Coupling slot, mm	51x4x2



- **Cold L-Band cavity BPM**
  - **ILC collaboration activity**
  - **Beam test of a prototype**
  - **Verify tuning, signal orthogonality and levels, resolution, reproducibility**
- **Waveguide Pickups**
  - **Horn antenna, waveguide & diode detector assembly**
  - **Available frequency range: 90-900 GHz**
  - **Simple setup for relative bunch length estimation (SLAC ESA, CERN CLIC)**

Summary

- **Advanced beam instruments play a mission critical role to characterize the beam parameters when performing current and future A0-Photoinjector AARD experiments.**
- **A comprehensive, challenging A0 instrumentation plan is proposed, it has some focus in the longitudinal domain:**
  - **Utilizing advanced optical, electro-optical and microwave state-of-the-art technologies.**
  - **Continuing ongoing developments, i.e. streak camera, *MP* interferometer, OTRI, and time-of-arrival diagnostics.**
  - **Start of new activities, i.e. CTR, EOS, HOM, cavity BPM, and waveguide pickup instrumentation.**
- **Local and international collaborations are established, and are crucial for the success of the program!**